Experimental validation of an elementary formula for estimating spatial resolution for optical transillumination imaging

Jeremy C. Hebden
University College London, Department of Medical Physics, 11-20 Capper Street, London WC1E 6JA, United Kingdom

Amir H. Gandjbakhche
National Institutes of Health, Division of Computer Research and Technology, Physical Sciences Laboratory, Bethesda, Maryland 20892

(Received 27 October 1994; accepted for publication 21 March 1995)

An inexpensive, safe, and effective diagnostic tool based on near-infrared radiation could offer some substantial advantages over existing medical imaging modalities. This has motivated considerable recent interest in the problem of imaging through highly scattering media.[1–9] A technique that has appeared particularly promising involves measuring the flight times of photons that scatter through the media, and using those having the shortest flight times to construct an image. This light will have been scattered along a path close to a straight line between the source and the detector and will have an intensity which is dependent upon the optical properties of the medium along that line. The temporal distributions of light transmitted through a scattering medium between two points on the surface is commonly known as the temporal point spread function (TPSF). Detection of the least-deviated component of the TPSF using coherent techniques has been achieved for media which are not too severely scattering.[2,3] For media more closely matching the scattering properties of human tissues, most imaging methods have involved illuminating the object with a short pulse of light and either enhancing the signal produced by the earliest-arriving photons[4,5] or measuring the TPSF directly.[6–9] Images through highly scattering objects have been presented as a function of the period of time, Δt, over which transmitted light is integrated.[8] It is found that, as expected, the highest spatial resolution is achieved using transmitted photons with the shortest flight times, a result which has also been demonstrated quantitatively by several investigators.[10–14]

For imaging a slab bounded by two parallel planes, spatial resolution represents a measure of the ability to resolve small objects located somewhere between the two surfaces. The resolution will depend on the spread of light in a plane parallel to the surfaces. For a confocal arrangement (see Fig. 1 of Gandjbakhche *et al.*[15]), where the area of illumination and the light collection area are both small, the spread is largest and the resolution worst at the center of the slab.[16] Although experiments have demonstrated the spatial resolution achievable for specific objects, until now there has been no proven reliable means of predicting the spatial resolution performance for an arbitrary medium using the confocal imaging geometry. However, a random walk model was recently developed which enables such predictions to be made.[15] This model is based on the random walk on an isotropic scattering lattice bounded by two absorbing planes. The characteristic scale of the lattice can be expressed in terms of the transport scattering coefficient μ_s', defined as $\mu_s(1-g)$, where μ_s is the scatter coefficient and g is the mean cosine of the scattering angle. A probability is calculated that a photon injected into a slab first crosses the midplane of the slab at a given point, and is then detected at a point on the exit plane immediately opposite the point of entry with a given path length through the slab. This model is described in detail elsewhere.[15,16] The model was employed to calculate the line spread function (LSF) of photons as they cross the midplane of a slab of finite thickness. Since the path length of the photons is proportional to their flight time, a relationship was obtained between the width of the LSF and the excess time t_{xs} by which a photon is delayed in reaching the detector compared with the time of flight without any scattering. By defining spatial resolution Δx as the full width of the LSF at one-tenth of the maximum intensity (FWTM), the following relationship was obtained between Δx and t_{xs}:

$$\Delta x = 1.19 \sqrt{\frac{c t_{xs}}{\mu_s'}}. \tag{1}$$

The constant c is the speed of light in the medium. Alternatively, if the resolution is defined as the full width at half maximum of the LSF, the multiplicative constant in the above expression would be 0.94. The model is valid in the diffuse approximation regime where the product of the thickness of the slab d and transport scattering coefficient is $\gg 1$. The model has already demonstrated very good agreement with the experimental data of Das *et al.*[9,16]

We now compare the result in Eq. (1) with two sets of experimental data which appear separately in the published literature.[10,11] A streak camera and picosecond pulse laser were used to obtain the edge response produced by an opaque mask embedded in the center of a transparent, rectangular box containing highly scattering, nonabsorbing solutions of latex microspheres. The transport scattering coefficients of the two solutions were 0.20 and 0.80 mm^{-1}, respectively. Edge responses were obtained as a function of an integration time Δt, which includes all photons with excess flight times up to a value of Δt. The edge responses were converted to LSFs and the spatial resolution, equal to the FWTM of the corresponding MTF, was estimated as a function of Δt. Further details on the experimentation and the theory may be found elsewhere.[10,11] In the case of the more highly scattering solution, a model fitting technique was applied to the raw data in order to enhance the signal to noise.[11] The spatial resolution Δx as a function of Δt for the two solutions is shown in Fig. 1. The solid lines represent the predicted relationship given by Eq. (1), with the assumption that we can substitute Δt for t_{xs}. This assumption should be reasonable if the mean excess flight time $\langle t_{xs} \rangle$ of the inte-

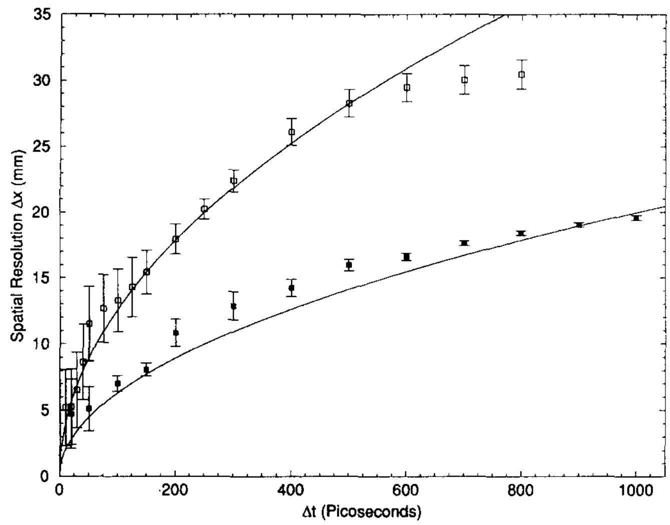

FIG. 1. The spatial resolution measured as a function of integration time for transport scattering coefficients of 0.20 (□) and 0.80 mm^{-1} (■) compared with the predictions of Eq. (1), assuming $t_{xs}=\Delta t$.

grated photons is close to the value of Δt. This will be approximately true for integrations over the earliest part of the TPSF where the detected intensity increases very rapidly with excess flight time, and most of the detected photons will have flight times at or near $t_{xs}=\Delta t$.

The agreement between Eq. (1) and the experimental data is good, perhaps surprisingly so considering the simplicity of the expression and the assumptions involved. The data confirms the prediction that the resolution achieved for a particular excess flight time improves as the degree of scatter increases. This effect is offset, however, by the corresponding rapid decrease in detected intensity. Put simply, the photons collected over an integration time Δt provide higher resolution information as μ_s' increases but they become rapidly fewer in number. Since the model assumes a slab infinite along dimensions perpendicular to the normal to each surface, some departure between the model and the data is expected at large integration times due to the finite size of the object. Longer flight time photons lost from the sides of the object will cause the spatial resolution Δx for a given integration time to be smaller than predicted. This may be partly responsible for the departure observed in Fig. 1 at longer Δt. However, as explained above, departure between the data and model at large Δt will also occur as the value of $\langle t_{xs}\rangle$ for detected photons becomes significantly less than Δt. In such a situation, the value of t_{xs} in Eq. (1) can be replaced with a computation of the true $\langle t_{xs}\rangle$, as described elsewhere.[15]

Our model predicts that given adequate signal, there is no limit to the achievable resolution. This may appear to conflict with the results of Moon and Reintjes,[17] but their model defines achievable resolution relative to a minimum detectable intensity threshold. Consequently, their estimate of resolution is strongly dependent upon thickness whereas our model produces an estimate independent of thickness. It should also be noted that their definition of resolution, based on the distribution of photons on the exit surface, is different, and does not involve a confocal geometry.

The consequences of the predictions of this model to medical imaging, and to breast imaging in particular, are discussed in detail elsewhere.[15] Uniform absorption in the medium effectively multiplies the TPSF by a function $\exp(-\mu_a c t_{xs})$, where μ_a is the absorption coefficient. Thus longer flight time photons are removed more than shorter ones. This does not alter the validity of Eq. (1), although by decreasing the value of $\langle t_{xs}\rangle$ for a given Δt, the integration time is decreased below which substituting Δt for t_{xs} in Eq. (1) is a reasonable approximation. The precise effects of absorption need to be investigated experimentally. Future experiments are also planned to investigate the prediction of Eq. (1) that the resolution is independent of slab thickness (providing $d\mu_s' \gg 1$). Nevertheless, the results shown here demonstrate that we already have a very simple tool for estimating with reasonable accuracy the spatial resolution achievable using time-resolved optical transillumination methods.

This research is supported in part by the Wellcome Trust.

[1]B. Chance and R. R. Alfano, Eds., *Photon Migration and Imaging in Random Media and Tissues*, Proc. Soc. Photo-Opt. Instrum. Eng. **1888** (1993).

[2]E. Leith, C. Chen, H. Chen, D. Dilworth, J. Lopez, J. Rudd, P.-C. Sun, J. Valdmanis, and G. Vossler, "Imaging through scattering media with holography," J. Opt. Soc. Am. A **9**, 1148–1153 (1992).

[3]K. Yoo, Q. Xing, and R. R. Alfano, "Imaging objects hidden in highly scattering media using femtosecond second-harmonic-generation cross-correlation time gating," Opt. Let. **16**, 1019–1021 (1991).

[4]L. Wang, P. P. Ho, C. Liu, G. Zhang, and R. R. Alfano, "Ballistic 2-D imaging through scattering walls using an ultrafast optical Kerr gate," Science **253**, 769–771 (1991).

[5]M. D. Duncan, R. Mahon, L. L. Tankersley, and J. Reintjes, "Time-gated imaging through scattering media using stimulated Raman amplification," Opt. Lett. **16**, 1868–1870 (1991).

[6]S. Andersson-Engels, R. Berg, S. Svanberg, and O. Jarlman, "Time-resolved transillumination for medical diagnostics," Opt. Lett. **15**, 1179–1181 (1990).

[7]D. A. Benaron and D. K. Stevenson, "Optical time-of-flight and absorbance imaging of biologic media," Science **259**, 1463–1466 (1993).

[8]J. C. Hebden, "Time-resolved imaging of opaque and transparent spheres embedded in a highly scattering medium," Appl. Opt. **32**, 3837–3841 (1993).

[9]B. B. Das, K. M. Yoo, and R. R. Alfano, "Ultrafast time-gated imaging in thick tissues: A step toward optical mammography," Opt. Lett. **18**, 1092–1094 (1993).

[10]J. C. Hebden, "Evaluating the spatial resolution performance of a time-resolved optical imaging system," Med. Phys. **19**, 1081–1087 (1992).

[11]J. C. Hebden, D. J. Hall, and D. T. Delpy, "Spatial resolution performance of a time resolved optical imaging system using temporal extrapolation," Med. Phys. **22**, 201–208 (1995).

[12]Y. Chen. "Characterization of the image resolution for the first-arriving-light method," Appl. Opt. **33**, 2544–2552 (1994).

[13]G. Mitic, J. Kölzer, J. Otto, E. Plies, G. Sölkner, and W. Zinth, "Time resolved transillumination of turbid media," Proc. SPIE **2082**, 26–32 (1993).

[14]K. J. Carson, Y. A. B. D. Wickramasinghe, and P. Rolfe, "Experimental study of spatial resolution for time resolved near infrared imaging," Proc. SPIE **2082**, 10–19 (1993).

[15]A. H. Gandjbakhche, R. Nossal, and R. F. Bonner, "Resolution limits for optical transillumination of abnormalities deeply embedded in tissues," Med. Phys. **21**, 185–191 (1994).

[16]A. H. Gandjbakhche, R. Nossal, and R. F. Bonner, "Theoretical study of resolution limits for time-resolved imaging of human breast," Proc. SPIE **2135**, 176–185 (1994).

[17]J. A. Moon and J. Reintjes, "Image resolution by use of multiply scattered light," Opt. Lett. **19**, 521–523 (1994).